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A Survey of the State of the Art and
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1. Introduction

In this one year renewal of NASA Contract No. 2-304, we have performed basic research, development, and implementation in the areas of modern estimation algorithms and digital communication systems. In the first area, we considered basic study on the conversion of general classes of practical signal processing algorithms into systolic array algorithms. In this area, we have four publications. We also studied the finite word length effects and convergence rates of lattice algorithms. There are two publications in this area. In the second area, we studied the use of efficient "importance sampling" simulation technique for the evaluation of digital communication system performances. There are two publications in this area.

2. Modern Estimation Algorithms and Applications

a. Systolic Array Algorithms

In paper [1], we considered a novel use of the modified square-root information filter approach to obtain a jointly time update and measurement update systolic Kalman filter. By using the matrix decomposition method, the Kalman filter is formulated as a SRIF data processing problem followed by a QR operation. Compared with the previously known covariance approach, this approach simplifies the computational structure and is more reliable when the system has a singular or near singular coefficient matrix. By skewing the order of input matrices, fully pipelined systolic Kalman filtering operation can be achieved. With the number of processing units of the $O(n^2)$, the system throughput rate is of the $O(n)$. The numerical properties of the systolic Kalman filtering algorithm under finite word length effect are studied via analysis and computer simulations, and are compared with those of conventional approaches.

In paper [2], by recognizing that various systolic QR algorithms can be delivered under an one-row time updating operation, we propose a generalized format for systolic QR estimation algorithm by taking the normalized form of two input data rows into consideration. From this approach, the basic relationship between Givens reduction and modified-Gram-Schmidt transformation can easily be understood. This generalized form enables us to derive new algorithms with efficiency. Based on this new formulation, a new systolic QR algorithm, called a modified fast

Givens algorithm (MFG), is proposed. It also can be shown that all existing systolic QR estimation algorithms can be classified as special cases under this generalized formulation. With systolic array implementation, comparison of computational complexity for different algorithms can be made by comparing the number of operations required in each processing unit of the systolic array. In this paper, we study all existing systolic QR algorithms by comparing both their computational and inter-cell connection complexities which are relevant in VLSI implementation. It is shown that the new MFG method has simpler computational and inter-cell connection complexities, and is well suited of VLSI systolic array implementation.

Due to advances in VLSI technology, there is much interest in using array processors to improve the throughput rate of various signal processing algorithms. In this paper [3], we propose a novel use of a square-root free linear systolic array structure that can perform the QR decomposition needed in the solution of the least-squares problems. Compared with the conventional triangular systolic array structure for LS estimation, the linear array has the advantage of requiring less area and is simpler for VLSI implementation.

In paper [4], new result on efficient forms of decoding convolutional codes based on the Viterbi algorithm by using systolic arrays are presented. Various properties of the convolutional codes are also discussed. A technique called strongly connected trellis decoding is introduced to increase the effi-

cient utilization of all the systolic array processors. The issues dealing with the composite branch metric generation, survivor updating, overall system architecture, throughput rate, and computational overhead ratio are also investigated. The scheme is applicable to both hard and soft decoding of any rate b/n convolutional codes. It is also shown that as the length of the code becomes large, the systolic Viterbi decoder maintains a regular and general interconnection structure as well as moderate throughput rate gain over the sequential Viterbi decoder.

b. Lattice Algorithms

Recursive least-squares lattice (RLSL) algorithms are used in many adaptive filtering and array processing problems. Reflection coefficients are important parameters that characterize the behaviors of these algorithms. In paper [5], we consider the spatial RLSL algorithm and study in detail the convergent properties as well as the finite precision round-off effects of the reflection coefficients. We first show that when the forgetting factor λ is set equal to one, the reflection coefficients can converge to a constant with probability one with the rate of convergence being $O(1/T^{3/2})$ where T is the number of terms involved. When $0 < \lambda < 1$, the reflection coefficients converge weakly. Furthermore, the variance of the reflection coefficient is decreased by increasing λ . Thus, under stationary conditions λ should be taken as large as possible, while under nonstationary conditions λ should be taken such that the depth of memory in the system matches the rate of change of nonstationarity. Under

finite word length constraint, should be taken to be less than some threshold, which is a function of the number of significant digits, such that the system can continuously adapt. In addition, we found the recursive form of computation for the reflection coefficients is generally better than under direct form of computation. In this paper, general analytical derivations and numerical results are presented on the convergent and round-off error properties of reflection coefficients in RLSL algorithms.

Ill conditions resulting from a wide range of signal power levels in an adaptive array system often lead to slow convergences. The Nolen beamforming network and direct matrix inverse method are two possible approaches to overcome such limitations. In addition, computational accuracy under a finite word length constraint accompanied by the ill-conditions is another important issue of interest. In paper [6], we consider the use of a spatial lattice algorithm (SLA) in a preprocessor of an adaptive array to achieve fast convergence rate, robust computational accurate performance, and simple modular form of implementation. While the spatial lattice algorithm used in this paper is based on the pioneering work of Lee, Morf, and Friedlander, an alternative simple and complete proof of the exact time update recursions using only algebraic techniques based on the Matrix Inverse Lemma is presented. This is in contrast to the geometric approach used in the original work of Lee, Morf, and Friedlander. In addition to the analytical development of the spatial lattice algorithm, extensive numerical results, including NBN and MGS,

for adaptive antenna arrays are presented and compared. These results show that the convergence rate of the spatial lattice algorithm is indeed rapid and is independent of the signal conditions. Moreover, under finite precision computations, the spatial lattice algorithm is significantly more robust than other methods and is essentially insensitive to the spread of the eigenvalues in the input sample covariance matrix. In addition, while the complexity of the spatial lattice algorithm is $O(K^2)$, where K is the number of array elements, the throughput rate is $O(K)$ due to its modular form. Thus, the spatial lattice algorithm appears to provide an attractive alternative to the previously known algorithms for high performance adaptive arrays.

3. Efficient Simulation of Digital Communication Systems

In paper [7], a new technique utilizing significantly lower number of samples to achieve convergence in the Monte Carlo simulation of digital communication systems based on the importance sampling (IS) technique is given. Basic formulas on the derivation of this technique as well as the proper selection of parameters and the associated estimation accuracy in our modified form of IS (denoted by MIS) are presented. Theoretical analysis and actual simulations showed that our approach can reduce significantly the required sample size in comparison with the conventional IS approach (denoted by CIS). For one dimensional as well as multi-dimensional Gaussian inputs, the estimation of bit error rate (BER) for our approach is uniformly better than that of previously known CIS approach. Specifically, for Gaussian inputs and a BER of $1E-10$ and a relative variance of 0.1, the ratio of sample size reduction of the known CIS as compared to our new MIS approaches for a zero-memory system is on the order of 12, while for systems with a memory of five and fifty samples, these ratios are 160 and 55000, respectively.

In paper [8], we derive an upper bound on the estimation variance and a lower bound on the improvement ratio of various importance sampling technique applied to the Monte Carlo simulation technique. On the basis of this bounding technique, we can find various sub-optimum IS parameters readily. Numerical results indicate that this technique yields tight and useful bounds applicable to generalized exponential distribution noise pdfs

(which include the Gaussian case) as well as linear and non-linear satellite communication systems with intersymbol interferences.

4. Publications in Contract Period

1. M.J. Chen and K. Yao, "Systolic Kalman Filtering based on QR Decomposition," Proc. SPIE, Vol. 826, Aug. 1987, pp.25-32.
2. M.J. Chen and K. Yao, "Comparison of QR Least-Squares Algorithms for Systolic Array Processing," Proc. Conf. on Inform. Sciences and Systems, March 1988
3. M.J. Chen and K. Yao, "Linear Systolic Array for Least-Squares Estimation," Proc. Inter. Conf. on Systolic Arrays, May 1988, pp. 83-92.
4. C.Y. Chang and K. Yao, "Systolic Array Processing of the Viterbi Algorithm," IEEE Trans. on Information Theory, Jan. 1989
5. S.H. An and K. Yao, "Convergent and Roundoff Error Properties of Reflection Coefficients in Adaptive Spatial Recursive Least-Squares Lattice Algorithm," IEEE Trans. on Circuits and System, Feb. 1988, pp.241-246.
6. S.H. An and K. Yao, "A Fast Convergent and Robust Spatial Lattice Algorithm for Adaptive Arrays," revised for IEEE Trans. on Aerospace and Electronics Systems, March 1988
7. D. Lu and K. Yao, "Improved Importance Sampling Technique for Efficient Simulation of Digital Communication Systems," IEEE Jour. on Selected Areas in Communication, Jan. 1988, pp. 67-75.
8. D. Lu and K. Yao, "On Some New Importance Sampling Results for Simulation of Non-Linear Digital Communication Systems," Proc. Conf. on Inform. Sciences and Systems, March 1988